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Redundancy and criticality based scheduling in Wireless Video Sensor Networks for monitoring critical areas

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Abstract

Applications for monitoring critical areas, based on Wireless Video Sensor Networks (WVSN), require simultaneously good level of coverage of the entire region of deployment, high frame capture speed and low power consumption in order to increase network lifetime. The question is how to find a tradeoff between these requirements. In this paper, we first propose two new approaches based on the cover set concept to help a node to find its redundancy level which is defined by the cardinality of its cover set. Then, thanks to a model based on behavior functions modeled by quadratic Bezier curves, we link the frame capture speed of video node to its redundancy level and to its criticality which is assigned to a node according to its position in the network. Border node has high criticality while interior one has low criticality. To identify boundary nodes, we propose an algorithm based on Greedy Perimeter Stateless Routing protocol (GPSR). Then, we propose an algorithm to schedule the activity of sensor nodes according to the redundancy level and criticality of each node. Finally, we introduce a new concept called backward border surveillance based on the cover set approach. Simulation results are presented to show performances of the two proposed approaches in terms of percentage of coverage, number of nodes with cover set, size of this latter, the impact of our scheduling algorithm on network lifetime and the incidence of backward border surveillance concept on quality of surveillance.

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Keywords: WVSN, boundary nodes, backward border surveillance, cover set, criticality, energy, GPSR.

1. Introduction

The availability of low-cost CMOS cameras has encouraged the development of Wireless Video Sensor Networks (WVSN) [10] which consist of set of sensor nodes with scarce resources (e.g. limited energy, memory and processing), equipped with miniaturized video cameras. In the last few years, WVSN have received a large attention in the research community, with applications in several domains such as military (battlefields, border surveillance), environment (fire detection), industrial process monitoring, health (automated assistance for elderly people) and home automation [1, 2, 3].

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This paper focuses on WVSN for Area Surveillance Applications such as an intrusion detection in a highly sensitive area (e.g. oil zone, frontier). Such applications have very specific needs due to their critical nature associated to security [2]. The first issue of prime importance is coverage. The second one is related to frame capture rate. The third one is related to energy which has a direct impact on both coverage and capture rate as it is not suitable to let all nodes in activity at the same time and with high capture rate due to the scarcity of this resource.

Fig. 1. Redundancy of FoV(s)

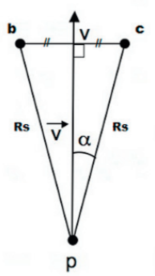

Fig. 2. FoV coverage model

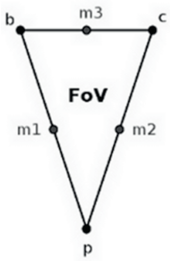

Fig. 3. Specific points of node's FoV

In WVSN where nodes are deployed randomly and with high density, the fields of view of the cameras can be redundant (cameras that monitor the same region as shown in Fig. 1). A common approach that exploits only redundancy is to define a subset of the deployed nodes to be active while the others can sleep. However, even if the criticality of the part of the area is high, it is not realistic (because of the big impact on the network liftetime) to consider that the nodes deployed in it should always capture at their maximum rate when they are in active mode. Indeed, it is desirable to adjust the capture rate according to the node cover set cardinality and the criticality of the part of the area. For this purpose, we have used a model based on behavior functions [1, 2, 7]. The result is the scheduling of nodes activity in order to garantee a high percentage of coverage of the initial covered area and an adjustable frame capture rate while reducing the energy consumption.The remainder of the article is organized as follows: Next section presents summary of related work. in section 3 we propose two new approaches able of finding node's cover set. Section 4 describes the model based on behavior functions modeled by quadratic Bezier curves. In section 5, we present our algorithm used by the sink to discover boundary nodes. We detail the redundancy and criticality based scheduling algorithm in section 6. Simulation results using the discrete event simulator OMNeT++ [11] are presented in section 7. We conclude our paper in section 8.

2. Related work

In order to ensure a high level of coverage of the monitored area while at the same time minimizing energy consumption and extending network liftime, the most commonly used approach is to select a subset of nodes to be active and keeping the remaining nodes (those whose area are covered by others) in sleep mode during each round. [1] introduces the concept of cover set to find the redundancy level of video node. A multiple cover set construction strategies are described and evaluated in terms of percentage of coverage, network liftime, intrusion stealth time and number of intrusion detection. Authors in [2] propose to take into account the application's criticality. They link it to the frame capture rate of video node. Therefore, a high criticality level indicates that the application requires a high frame capture rate while a low criticality level doesn't. They also describe the risk-based scheduling in WVSN. Indeed, different parts of the monitored area may have different risk levels. The same paper presents a model based on behavior functions which allows to link the frame capture speed of video node to its redundancy level defined by the cardinality of its cover set and to the application's criticality. The result is that node with a large cover set will capture faster because it can be easily replaced if it die. By contrast, the node with a small cover set should preserve its energy. However, when the risk level increases, the capture rate increases even for nodes with small cover set.

In our case, we first propose two new approaches VMA_1 and VMA_2 [9] allowing a node to compute its cover set. Then, we propose an algorithm based on Greedy Perimeter Stateless Routing (GPSR) protocol, which is launched by the sink node at the begining of simulation in order to discorver network boundary. Boundary nodes are assigned high criticality (high capture rate) while low criticality is assigned to interior nodes. Some of these latter which have a high cover set cardinality can still capture at maximum rate (act as sentinels). Finally, an activity scheduling algorithm based on cover set cardinality and criticality of each node is detailed.

3. New approaches for calculating cover set

3.1. FoV Coverage model

In traditional Wireless Sensor Networks (WSN), sensor nodes collect information from environment within a pre-defined sensing range, i.e a roughly circular area defined by the type of sensor being used [1]. In WVSN, the concept of sensing range is replaced with the camera's FoV which is commonly defined as an isosceles triangle denoted by a 4-tuple $v(p, d, \overrightarrow{v}, \alpha)$ [1]. P represents the random and static position of video node v, d is the distance pv (dePth of View, (PV)), $\overrightarrow{v}$, called line of sight, is the vector representing the random and static direction of camera's FoV and α is the half angle of vision (2α is the Angle of Vision, (AV)).Fig. 2 illustrates the representation of the FoV of node v in this model.

3.2. Cover set concept

A cover set $Co_i(v)$ of a video node v is defined as subset of redundant neighbor nodes such that $\bigcup_{v' \in Co_i(v)}(v'$'s FoV area) covers v 's FoV area. $Co(v)$ is defined as the set of all the cover sets of node v [1].

3.3. Proposed approaches

The two proposed approaches, denoted VMA_1 and VMA_2, use specific points of the isosceles triangle (pbc), shown in Fig. 2, to determine node's cover sets ($Co_i(v)$) that may not completely cover v's FoV but a high percentage of it. Fig. 3 illustrates the specific points used by VMA_1 and VMA_2, namely triangle vertices p, b and c and the midpoints of its sides, denoted respectively by $m1$, $m2$ and $m3$.

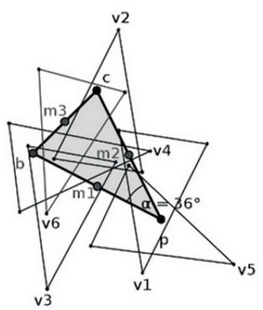

Fig. 4. Example

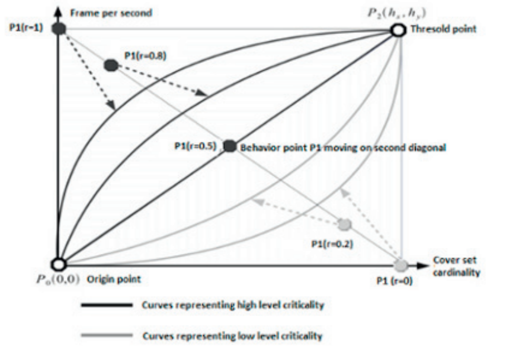

Fig. 5. BV function curves when P_1 is moving along the second diagonal

3.3.1. VMA_1

v 's FoV is covered by a set $Co_i(v) \in Co(v)$ if the two following conditions are satisfied:

1. $\forall v' \in Co_i(v)$, v' covers at least one vertex and at least one midpoint.
2. p, b, c and the three midpoints $m1$, $m2$ and $m3$ are all covered by elements of $Co_i(v)$.

Node v computes its $Co(v)$ as follows: it starts by finding sets: $P/B/C/M1/M2/M3 = \{v' \in N(v)/v'$ covers points $p/b/c/m1/m2/m3\}$, $P \times B \times C$ and $M1 \times M2 \times M3$, where $N(v)$ is the set of its neighbors.The $Co(v)$ is then given by:

$$Co(v) = (P \times B \times C) \cap (M1 \times M2 \times M3) \quad (1)$$

3.3.2. VMA_2

v 's FoV is covered by a set $Co_i(v) \in Co(v)$ if the two following conditions are satisfied:

1. $\forall v' \in Co_i(v)$, v' covers at least one vertex and at least one midpoint.
2. p, b, and c are all covered by elements of $Co_i(v)$.

Node v computes its $Co(v)$ as follows: it starts by finding sets: $P/B/C/M1/M2/M3 = \{v' \in N(v)/v'$ covers points $p/b/c/m1/m2/m3\}$, $E1 = P \cap (M1 \cup M2 \cup M3)$, $E2 = B \cap (M1 \cup M2 \cup M3)$ and $E3 = C \cap (M1 \cup M2 \cup M3)$, where $N(v)$ is the set of its neighbors. The $Co(v)$ is then given by:

$$Co(v) = E1 \times E2 \times E3. \quad (2)$$

3.3.3. Example

Fig. 4 shows an example for calculating $Co(v)$ using the two proposed approaches.

1. Using VMA_1
   (a) $P = \{v1, v5\}$, $B = \{v3, v4\}$, $C = \{v2, v6\}$, $M1 = \{v3\}$, $M2 = \{v1, v2, v4\}$, $M3 = \{v6\}$.
   (b) $Co(v) = (P \times B \times C) \cap (M1 \times M2 \times M3) = \{v3, v1, v6\}$.

2. Using VMA_2
   (a) $P = \{v1, v5\}$, $B = \{v3, v4\}$, $C = \{v2, v6\}$, $M1 = \{v3\}$, $M2 = \{v1, v2, v4\}$, $M3 = \{v6\}$.
   (b) $Co(v) = E1 \times E2 \times E3 = \{(v1, v3, v2), (v1, v3, v6), (v1, v4, v2), (v1, v4, v6)\}$.

4. Model based on Bézier curves

Bézier curve is a parametric form to draw a smooth curve. It is fulfilled through some points $P_0, P_1, \cdots, P_n$, starting at P_0, going towards $P_1, \cdots, P_{n-1}$ and terminating at P_n.

The model we used [2, 7, 8] is based on quadratic Bézier curves (three points) which is given by:

$$B(t) = (1-t)^2 P_0 + 2t(1-t)P_1 + t^2 P_2, \quad t \in [0, 1] \quad (3)$$

where $P_0(0, 0)$ is the origin, $P_1(b_x, b_y)$ ($0 \le b_x \le h_x$ and $0 \le b_y \le h_y$) is the behavior point and $P_2(h_x, h_y)$ is the threshold point ($h_x > 0$ and $h_y > 0$ are respectively the highest cover set cardinality and frame capture rate). The parametric equation obtained from equation (3) is:

$$\begin{cases} B_x(t) = 2t(1-t)b_x + t^2 h_x \\ B_y t = 2t(1-t)b_y + t^2 h_y \end{cases} \quad (4)$$

Then, equation (4) is modified to obtain the following cartesian function BV (Behavior Function, P_1 is called behavior point) of the form $Y = f(X)$:

$$BV : [0, h_x] -> [0, h_y]$$

$$X -> Y = BV_{P_1,P_2}(X) =$$

$$\begin{cases} \frac{h_y - 2b_y}{4b_x^2} X^2 + \frac{b_y}{b_x} X, \quad if(h_x - 2b_x = 0) \\ (h_y - 2b_y)t_1^2 + 2b_y t_1, \quad if(h_x - 2b_x \neq 0) \end{cases} \quad (5)$$

where:

$$\begin{cases} t_1 = \frac{-b_x + \sqrt{b_x^2 - 2b_x X + h_x * X}}{h_x - 2b_x} \\ (0 \leq b_x \leq h_x) \\ (0 \leq X \leq h_x) \\ (h_x > 0) \end{cases} \tag{6}$$

Therefore, the BV function takes as input the cadinality of the node's coverset (X) and returns the corresponding frame capture rate (Y) which is linked to the area criticality $r \in [0, 1]$. the latter is represented by the position of the behavior point P_1:

$$\begin{cases} r = 0, & P_1 = (h_x, 0) \\ r = 1, & P_1 = (0, h_y) \end{cases} \tag{7}$$

So, as illustrated in Fig. 5, the BV function curve will take concave or convex form depending on P_1 position on the second diagonal of the rectangle defined by P_0 and P_2. The second diagonal is a line defined by points $P_1(r = 0)$ and $P_1(r = 1)$ (see equation (7)). Therefore, its equation is:

$$Y = \frac{-h_y}{h_x} X + h_y \tag{8}$$

In order to fix P_1 on this line, the function C is defined as follows:

$$\begin{aligned} C : [0, 1] \quad &-> \quad [0, h_x] * [0, hy] \\ r \quad &-> \quad C(r) = \begin{cases} b_x = -h_x * r + h_x \\ b_y = hy * r \end{cases} \end{aligned} \tag{9}$$

5. Border nodes discovery algorithm

Our Algorithm is based on GPSR protocol [3, 4]. To find border nodes, the sink sends a packet to a fictitious destination [5, 6] which is a node that is disconnected from all other nodes and is the closest to the sink starting from the orthogonal projection of the sink on each side of the rectangle representing the deployment field. The packet is sent using the greedy or perimeter mode of the GPSR protocol. The Greedy mode is executed on the initial unit graph. However, the perimeter is executed on planarized graph (Gabriel Graph) using the right hand rule. Because the fictitious destination is unreachable, the packet makes necessary a tour and returns to the initial node. During this tour, border nodes are identified. (See illustrations below, network of 80 nodes with radio range = $25m$)

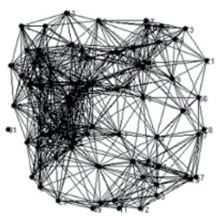

Fig. 6. Unit Graph

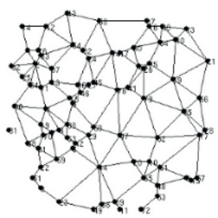

Fig. 7. Gabriel Graph

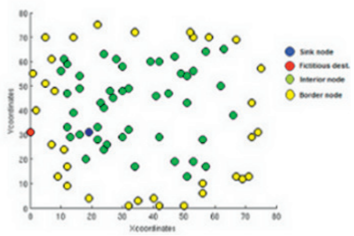

Fig. 8. Border nodes

6. Scheduling Algorithm

The objective of this algorithm is to minimize the number of active nodes and adjust their frame capture rate according to their cover set cardinality and area criticality while ensuring the whole coverage area.

Algorithm 1 Border nodes discovery algorithm

Require: nodes positions
Ensure: Identify border nodes
build initial graph from network description file (*ned file*)
Planarize initial graph (*build Gabriel graph*)
Find Fictitious Destination (FD)
next_node ← GPSR_FORWARD(sink, FD, P) /* Sink node send a packet P to FD*/
while (next_node≠ -1) **do**
  Identify next_node as border node
  next_node←GPSR_FORWARD(next_node, FD, P)
end while
Assign a high criticality level to border nodes

Border nodes do not excute this algorithm. They are assigned a high criticality level and they still always active. They have the responsability to alert other nodes when an intrusion is detected. Before a border node dies, it elects one cover set from its table of cover sets to replace it by assigning a high criticality to all nodes in it. So, we define a new concept called a backward border surveillance based on cover set approach. The cover set is choosed according to its percentage of coverage of the area covered initially by border node or according to its residual energy. This election is what we call the decline of the border or backward border based on cover set concept. Indeed, we exploit the fact that nodes have initially compute their cover sets. So, instead of starting the boder nodes discovery algorithm each time a border node dies, we use this concept.

Algorithm 2 Redundancy and criticality based Scheduling algorithm

$valid\_Co_i(v) \leftarrow 1$ /*v is itself a valid coverset*/
$i \leftarrow 1$
while $i \leq card(Co(v))$ **do**
  if $v' \in Co_i(v)$ **then**
    if v' has decided to go to sleep mode **then**
      $Co_i(v)$ becomes invalid
    else {v' has decided to be active}
      if $\forall\ v_1 \in Co_i(v)$, v_1 is active **then**
        $Co_i(v)$ is valid
        $valid\_Co_i(v) \leftarrow valid\_Co_i(v) + 1$
      else {$\exists\ v_1 \in Co_i(v)/v_1$ is in sleep mode}
        $Co_i(v)$ is invalid
      end if
    end if
  else
    if $\forall v_1 \in Co_i(v), v_1$ is active **then**
      $valid\_Co_i(v) \leftarrow valid\_Co_i(v) + 1$
    end if
  end if
  $i \leftarrow i + 1$
end while
if $valid\_Co_i(v) > 1$ **then**
  v decides to go to sleep mode and sends its decision to its neighbors
else
  v computes its capture rate according to $valid\_Co_i(v)$ and area criticality, decides to remain active and sends its decision to its neighbors
end if

7. Simulation results

To evaluate the performance results, we make a series of simulation under the OMNeT++ simulator. We consider randomly deployed video wireless sensor network modeled as unit graph which nodes are points in the plane and two nodes can communicate if the distance between them is less than a fixed unit. Battery capacity of each node is decreased by 1 unit per captured frame. Table 1 summarizes the simulation parameters.

Parameters	Values
Monitored area	$75m \times 75m$
Number of nodes	80, 150 200, 300
Position and direction of nodes	Random and static
Radio range, AV, PV	$25m$, $36°$, $25m$
Maximum capture rate, Criticality	3 fps, [0, 1]
Cover set cardinality	$1 \leq$ card(Co(v))≤ 6
Initial battery capacity	100 units
Number of simultions for each scenario	20

Table 1. Simulation parameters

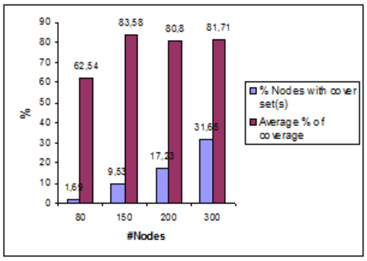

Fig. 9. VMA_1 's Performances

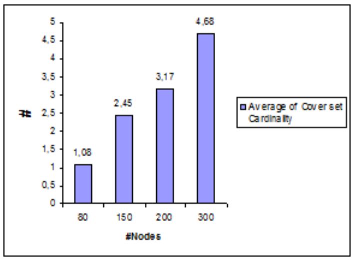

Fig. 10. VMA_1 's Performances

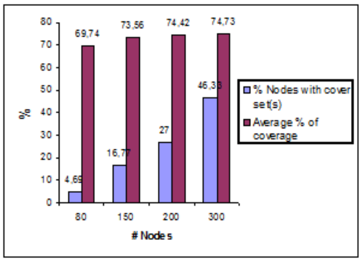

Fig. 11. VMA_2 's Performances

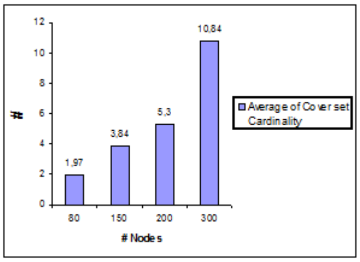

Fig. 12. VMA_2 's Performances

The first inference that can be drawn from the histograms depicted by figures 9, 10, 11 and 12 is that performances of VMA_1 and VMA_2 increase significantly when number of nodes increases. The proposed approaches allow a good level of coverage of the area of interest up to 83% for VMA_1 and 74% for VMA_2. The high level of coverage allowed by VMA_1 compared to the coverage allowed by VMA_2 is due to the second condition imposed when calculating a cover set using VMA_1. For the same reason, the percentage of nodes with cover set and the average of cover set cardinality are affected. Indeed, these two parameters increase when using VMA_2. This has a direct impact on the network lifetime since a lot of nodes could be in sleep mode. Table 2 and Table 3 illustrate the performance results of our scheduling algorithm in terms

r	fps (average)	lifetime (sec)
0.2	0.15	1340
0.5	0.50	410
0.9	1.57	130

Table 2. Performances of redundancy and criticality based scheduling algorithm (#Nodes=80, Approach=VMA_1)

r	fps (average)	lifetime (sec)
0.2	0.17	1340
0.5	0.52	410
0.9	1.60	130

Table 3. Performances redundancy and criticality based scheduling algorithm (#Nodes=80, Approach=VMA_2)

r (Interior nodes)	r (Border nodes)	fps (average)	lifetime (sec)
0.2	0.7	0.93	110
0.1	0.8	1.22	90

Table 4. Performances in term of quality of surveillance of the backward border approach (Number of nodes=80)

of network lifetime and frame capture rate when using respectively VMA_1 and VMA_2. Table 4 indicates average capture rate and network lifetime when varying criticality for border nodes and interior nodes.

8. Conclusion

In this paper we try to find a tradeoff between two essential needs of critical area surveillance applications, namely coverage and network lifetime. We propose two new approaches for calculating cover set. Then, we use a model that links the frame capture speed to the coverset's cadinality and the area criticality. A scheduling algorithm based on this model is proposed. Performance results of VMA_1 and VMA_2, in terms of percentage of coverage, number of nodes with cover set and the size of this latter, the impact of the proposed scheduling algorithm on network lifetime are encouraging. Also, the introduction of the new concept of backward border surveillance allows the enhancement of the quality of surveillance. Our goal in near future is to modify our proposed scheduling algorithm in order to manage the activity of nodes taking into account the MAC protocol behaviour (e.g. S-MAC, T-MAC or X-MAC).

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